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Signal-to-Noise Dependence on the Received Object and Background Power in Laser Systems

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The influence of the solar radiation and object reflectance on the power received from an object and background by laser systems, on the wavelength of 1.064 μm, is analyzed. The level of the power received from an object and background, limited by the receiver field of view, depends on solar irradiance variation, and object and background reflectance. The dynamic range of the received optical noise power is about 127 dB. The level of the received optical power reflected from the object and background, defines signal-to-noise ratio of the detector. The change of the signal-to-noise ratio for constant value of the received reflected laser radiation (P_s), as the function of the background power change (P_B), is analyzed. The maximal change of the signal-to-noise ratio of about 2 dB, is obtained for $P_s \approx P_B$.

Key words: **lasers, optical power, solar radiation, radiation influence, light reflection, reflection coefficient, irradiance, signal-to-noise ratio.**

Introduction

IN the rangefinder laser systems and systems for tracking of laser irradiated objects, the laser beam divergence is much smaller than the receiver field of view. Apart from the power reflected from the object, laser systems also gather the solar radiation reflected from the object and backround, as well as albedo from atmospheric scattering [1]. The received power of solar radiation reflected from the background has influence on the photodiode quantum noise and signal-to-noise ratio [2]. The level of the received power depends on the day time, season, geographic coordinates, atmospheric conditions and geometric configuration of object-receiver-Sun system in the moment of signal measurement [3]. The received power of reflected solar radiation from background is direct proportional to product of the spectral solar irradiance and background reflectance [2].

In this paper, the solar irradiance on the Earth surface and background reflectance are analyzed. The received optical power for calculated values for solar irradiance and measured reflectance of the natural environment surfaces, is defined.

The Estimation of the Solar Irradiance on the Earth Surface

The spectral density of radiation power or solar spectral emissivity, if we assume that the Sun is a black body, is calculated from Plank's law

$$M_\lambda = \frac{c_1}{\lambda^5}\frac{1}{\exp(c_2/\lambda T)-1} \tag{1}$$

where c_1 and c_2 are the first and the second radiation constant $c_1 = 3.7415\cdot 10^8$ Wm$^{-2}\mu$m^4 and $c_2 = 1.43879\cdot 10^4$ Kμm, λ is the wavelength in μm, and T is the absolute temperature in $K\left(T = 5900\,\text{K}\right)$. The spectral solar irradiance on the Earth surface, is

$$E_\lambda^S = M_\lambda^S \frac{R_S^2}{R_{ZS}^2}\tau_\lambda \tag{2}$$

where R_S is the Sun mean radius $\left(R_S = 696000\ \text{km}\right)$, R_{ZS} is the Earth-Sun distance, τ_λ is the spectral transmissivity of the atmosphere.

The mean value or average distance from observer on the Earth to the Sun surface, depends on the season and the Sun position relative to the observer. In Fig.1, the basic geometry for determinating R_{ZS} distance in the daytime, relative to observer on the Earth is shown.

In Fig.1, we mark the following distances as: the mean Earth radius - $R_z = 6367.25\,\text{km}$, the mean Earth - Sun distance - $R_0 = 149.6\cdot 10^6\,\text{km}$, and γ as the angle of the Sun position relative to the normal on the Earth surface. The average Earth - Sun distance, from Fig.1, as function of the angle γ, can be expressed in the following manner:

$$R_{ZS} = R_0\sqrt{1+2R_z/R_0+(R_z\cos\gamma/R_0)^2} - R_z\cos\gamma \tag{3}$$

Replacing relation (3) in (2), we get the spectral solar irradiance on the Earth surface. The solar irradiance, in the

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case of ideal atmosphere and equivalent sun temperature of 5900 K, on wavelength of 1.064 μm as the function of angular position of the Sun relative to the observer on the Earth, for three Earth-Sun distances, is presented in Fig.2.

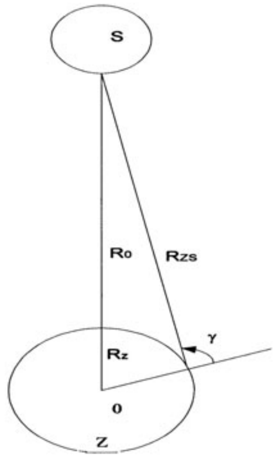

Figure 1. The Sun position relative to the Earth surface.

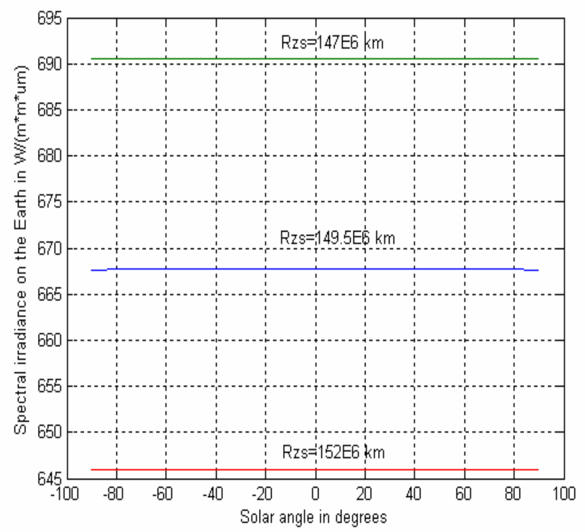

Figure 2. The spectral irradiance on λ =1.064 μm , as the function of angular position of the Sun, in the case of ideal atmosphere, for three Earth-Sun distances.

From Fig.2 is seen, that the solar spectral irradiance depends on Earth-Sun distance during the year, and it is independent of the angle γ , in the case of ideal atmosphere.

However, the solar radiation power propagates through the atmosphere, and a part of it is absorbed, a part is reflected, and a part is refracted, so that the value of the spectral irradiance on the Earth surface is changed depending on the atmospheric composition. The atmospheric transmissivity is estimated on the base of optical visibility on 0.55 μm . The spectral atmospheric transmissivity is given by [3]:

$$\tau_\lambda = \exp(-\beta_\lambda z) \tag{4}$$

where β_λ is the spectral extinction coefficient and z is the path passed through the atmosphere.

The spectral extinction coefficient, as the function of the optical visibility, is [3]:

$$\beta_\lambda = \frac{3,912}{R_V}\left(\frac{0,55}{\lambda}\right)^q \tag{5}$$

where R_V is the optical visibility on 0.55 μm .

The parameter q is calculated from relation $q = 0.58(R_V)^{1/3}$. The solar irradiance on the Earth surface, for atmospheric layer H_a thick, is calculated from relation (1)-(5). The distance passed through the atmospheric layer in (4) is defined from relation which is similar to (3), where R_0 is symbolically replaced with H_a, and R_{ZS} with z . The solar spectral irradiance (on 1.064 μm) on the Earth surface, for minimal, average and maximal annual Earth-Sun distance, $H_a = 6$ km , $R_v = 23$ km and 5 km , is presented in Fig.3.

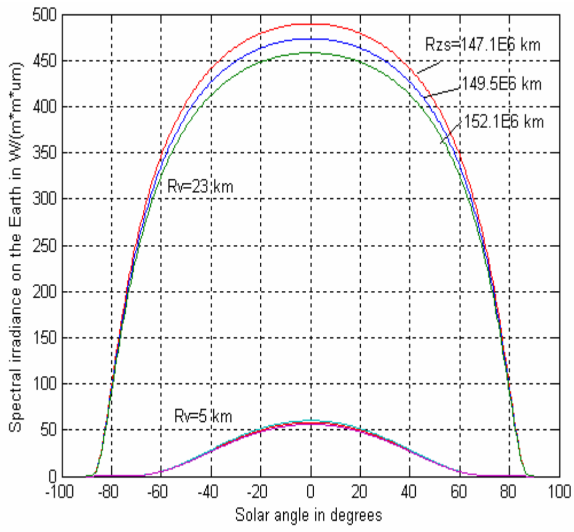

Figure 3. The solar irradiance on $\lambda = 1.064$ μm , for $H_a = 6$ km , and optical visibility of $R_v = 23$ km and 5 km.

From Fig.3 is seen that the solar irradiance on the Earth surface is changed considerably relative to ideal atmospheric conditions ($H_a = 0$ km Fig.2). The irradiance is considerably smaller for optical visibility of 5 km than in case when optical visibility is 23 km. The irradiance value decreases rapidly when the angular position of Sun is greater than 60°, although the atmospheric layer is only 6 km thick.

In the night, the solar radiation is reflected from the Moon surface and reaches the earth surface. The spectral irradiance on the Earth surface from solar radiation reflected from the Moon, is calculated from relation [4]

$$E_\lambda^M = \tau_\lambda M_\lambda^S \frac{R_S^2}{R_{SM}^2} \rho_M \frac{R_M^2}{R_{ZM}^2} \tag{6}$$

where R_{SM} is the average Sun-Moon distance, R_M is the average Moon radius $(R_M = 3473.3\,\text{km})$, ρ_M is the Moon surface reflectance, R_{ZS} is the average Earth-Moon distance $(R_{ZM} = 384.4 \cdot 10^3\ \text{km})$.

In Fig.4, is presented one geometric Sun-Earth-Moon configuration, suitable for calculating irradiance on the Earth surface that originates from solar radiation reflected from the Moon.

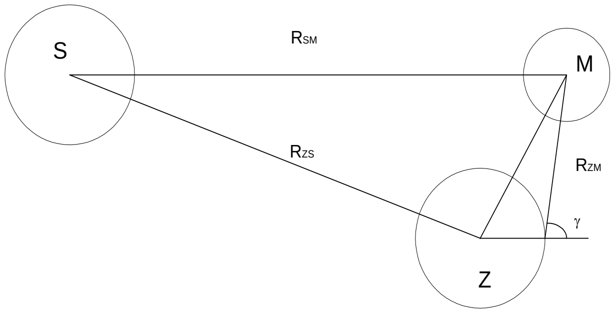

Figure 4. Geometric Sun-Earth-Moon configuration.

The spectral irradiance on the Earth surface is calculated for one Sun-Moon-Earth configuration, in the case where the Sun-Moon distance is approximately $R_{SM} = R_{ZS} + R_{ZM}$, $\left(R_{ZS} = 150.1 \cdot 10^6 \text{ km and } R_{ZM} = 384.4 \cdot 10^3 \text{ km}\right)$. The spectral irradiance on 1.064μm, for three phases of the Moon and Moon surface reflectance of 0,1 [4], atmospheric layer $H_a = 6$ km and optical visibility of 23 km and 5 km, is showed in Fig.5. The Fig.5 is obtained in the same manner as the Fig.3.

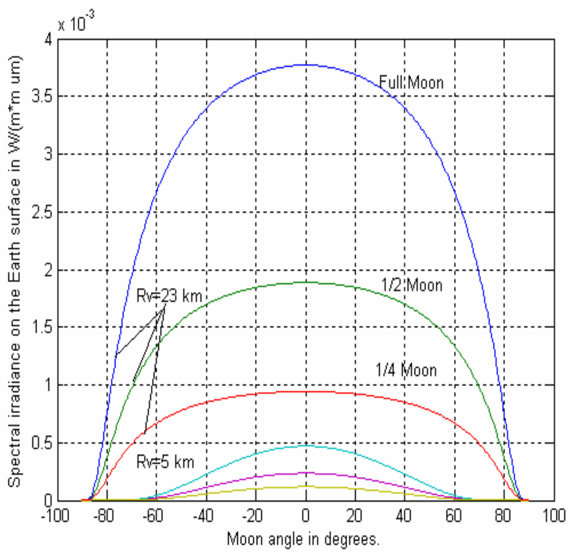

Figure 5. The spectral irradiance (on $\lambda = 1.064\,\mu\text{m}$) on the Earth surface for three Moon phases, $H_a = 6\,\text{km}$, $R_v = 23$ km and 5 km.

From Fig.5 is seen, that the spectral irradiance is changed with Moon phases and with Moon angular position relative to observer, under the condition that the Moon is irradiated with solar radiation. For optimal conditions of propagating through the atmosphere (for good optical visibility $R_v = 23$ km and relatively thin atmospheric sheet $H_a = 6$ km), the spectral irradiance is small $(1-4)$ mWm^{-2}μm^{-1}, depending on Moon phases and Moon angular position. However, for small optical visibility $R_v = 5$ km and $H_a = 6$ km, the irradiance is smaller than 0.5 mWm^{-2}μm^{-1} for all Moon phases, and rapidly decreases with the increasing of the Moon angular position, as presented in Fig.5.

The big spectral solar irradiance dynamics, for 1.064 μm, on the Earth surface, is the consequence of the Earth rotation around its own axis and the atmospheric conditions. Under the same conditions of atmospheric propagation ($R_v = 23$ km and $H_a = 6$ km), the maximal solar spectral irradiance on the Earth surface is less than 4 mWm^{-2}μm^{-1} in the night, and less than 500 mWm^{-2}μm^{-1}, in the daytime.

The Reflectance

The reflectance of surface depends on the radiation wavelength and the surface condition (roughness, waviness, ...). The irradiated surfaces differ in appearance (topography of surfaces) and in existence of vegetation, kind of soil, objects, ... It is very common, that the results for many surfaces are estimated on the bases of the experimental data.

The reflectance values used in recognition studies are obtained with spectrometers [5] and [6]. Also, there is a problem in connecting theoretical and real experimental results. Due to the fact that the rough surfaces scatter the light very irregularly, into the hemisphere in front of a reflective object, it is necessary to gather (or integrate) a large fraction of the light scattered into the hemisphere.

The measurement of the directional-hemispherical reflectance may be considered as the fundamental reflectance measurement, because it provides the calibration of reference surfaces used in remote sensing field and laboratory work. The measurements are routinely made by use of dual-beam spectroradiometer or spectrophotometer [5]. A common assumption for rough surfaces is that the rough surfaces are isotropic or pure diffuse.

The result of diffuse surface scattering may be very complex (the incident light is scattered into the hemisphere). It is usually assumed that the scattered radiance is a constant. This means that the scattered power/unit solid angle decreases as cosine of scattered angle. If the scattered intensity is proportional to cosine of scattered angle, then the bidirectional reflectance distribution function [7] is a constant. The samples that scatter in this manner are known as Lambertian samples.

Spectrophotometric measurements of some interesting samples in Military Technical Institute Laboratory were made. The pure diffuse reflection measurements (specular component is eliminated) are made by Perkin-Elmer UV/VIS/NIR Lambda 9 spectrometer, with integrating sphere (60 mm), which has a photomultiplicator in the visible domain and PbS detector in the infra-red (IR) domain. The spectrometer is equiped with tungsten-halogen source (visible and near IR domain) and deuterium source for the UV domain. The waveband for UV/VIS domain is (185-900) nm, and for near IR domain (900-3200) nm. The output devices of the spectrometer are video display and ploter for graphic presentation of results. The graphic apcise is the wavelength or wavenumber, and ordinate is the measured parameter: absorptance, transmitance, reflectance, in %. The sample size is 4 cm×4 cm, thick up to 1.5 cm. The samples have to be flat (not curved). The measurement of sample reflectance, in the spectral band (0.4-1.5) μm is performed in the spectrometric laboratory. The results are shown in Table 1 for wavelength of 1.064 μm.

It is seen from the table that the reflectance is considerably changed, dependent on the kind of the irradiated matter. The range of the tile and building blocks reflectance, from 0.72 to 0.8, is explained by slightly changeable chemical composition or surface final treatment.

The results from Table 1 are in good agreement with reflectance from references. The values for reflectance of some samples are given in [6]: concrete 46%, asphalt 23%, soil 30%, gravel 30%.

Table 1. The reflectance on λ = 1.064 μm for some natural surfaces.

No.	Sample	ρ_λ on $\lambda = 1.064\,\mu\text{m}$
1	Concrete	0.40
2	Tile "Toza Marković", Kikinda	0.74
3	Building blocks, Kanjiža	0.78
4	Bricks, "Polet", Novi Bečej	0.72
5	Anterior stone, light brown color	0.51
6	Tegola Canadese (green)	0.19
7	Carton	0.78
8	Wood (without coatings)	0.91

Dynamics of the Received Background Power

One part of the total received power in the laser systems (rangefinders, designators,…), is the power of scattered background radiation [1], [2]. If we assume that the object surface and background are Lambertian reflectors, relation for received background power, P_B, is given by [1]:

$$P_B = \frac{\pi E_\lambda^S \rho_\lambda \beta_R^2 D_R^2 \Delta_\lambda T_R T_F \exp(-\sigma R_B)}{16} \qquad (7)$$

where E_λ^S is the solar spectral irradiance ($\text{Wm}^{-2}\mu\text{m}^{-1}$), ρ_λ is the spectral reflectance, β_R is the total receiver field of view (rad), D_R is the receiver clear aperture diameter (m), Δ_λ is the receiver spectral filter bandpass (m), T_R is the transmission through the receiver optics, T_F is the receiver spectral filter transmission, σ is the atmospheric extinction coefficient (1/km), R_B is the slant range from background surface to the receiver (m).

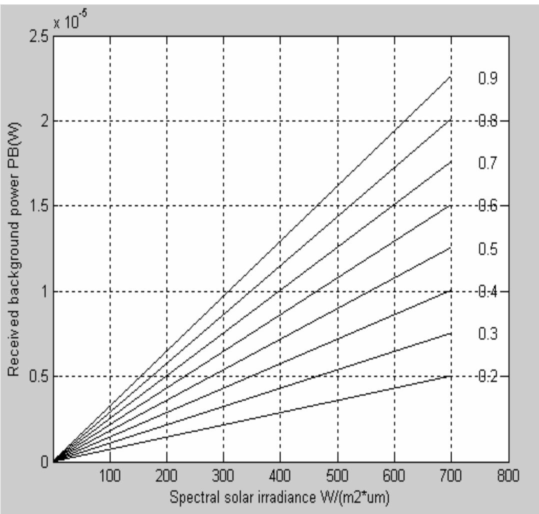

Figure 6. The change of received optical background power with spectral solar irradiance for various values of background reflectance.

In this paper, the influence of parameters E_λ^S and ρ_λ on the background power is analyzed, and numeral values for other parameters are taken from [2]: $\beta_R = 150\,\text{mrad}$; $D_R = 0.0254\,\text{m}$; $\Delta_\lambda = 200 \cdot 10^{-10}\,\text{m}$; $T_R = 0.9$; $T_F = 0.7$. In the case of the small receiver-backround surface range (order of one meter), the exponential expression in (7) is negligible. The solar spectral irradiance on the Earth surface is changed from 0 (theoretical value) to 700 $\text{Wm}^{-2}\,\mu\text{m}^{-1}$. In the night, when the solar radiation is reflected from the Moon surface, the spectral irradiance is order of $\text{mWm}^{-2}\,\mu\text{m}^{-1}$, and about 500 $\text{Wm}^{-2}\,\mu\text{m}^{-1}$, in the daytime. The received background power with neglected exponential expression in (7), for E^S_λ =(0.001–700) $\text{Wm}^{-2}\mu\text{m}^{-1}$ and $\rho_\lambda = 0.2 - 0.9$, is presented in Fig.6.

From the Fig.6, it is obvious that there is a great change of received background power with both parameters. The minimal received background power is order of pW, for $\rho_\lambda = 0.2$ and $E_\lambda^S = 1\,\text{mWm}^{-2}\mu\text{m}^{-1}$.

The received background power dynamics is direct proportional to dynamics of product $\rho_\lambda \cdot E_\lambda^S$, as is obvious from (7). The dynamics of the received background power (in calculated range of E_λ^S and in measured range of ρ_λ) is given by:

$$D = 20\log\frac{P_{B\max}}{P_{B\min}} = 20\log\frac{0,9\cdot 500}{0,2\cdot 10^{-3}} \approx 127\ dB$$

where the definition of current ratio in dB is applied, since the current in output of inverse polarized photodiode is direct proportional to the incident optical power.

The Influence of Background Power on SNR in the Presence of Laser Pulse

The received background power has influence only on the photodiode noise power, through the total received optical power $P_0 = P_s + P_B$, where P_S is the received laser power reflected from object [2].

Provided that the quadrant photodiode PIN type is an active element in receiver, the signal-to-noise ratio (*SNR*) in one channel is expressed by [1, 2]:

$$SNR = \frac{(R_K P_S)^2}{2q\left[I_D + (P_S + P_B)R_K\right]B + \frac{4kTB}{R_L}} \qquad (8)$$

where P_S is the received laser power reflected from the object (W), R_K is the responsivity of quadrant photodiode (A/W), q is the electron charge (C), I_D is the photodiode dark current (A), P_B is the received background power (W), k is the Boltzmann's constant (J/K), T is the absolute temperature (K), R_L is the channel resistance of the quadrant photodiode (Ω), B is the receiver bandwidth (Hz).

The total *SNR*, for four photodiode channels, if we use the ideal electronics (transimpedance amplifier, device for adding) and noise factor of the overall electronic block greater than 1, is:

$$SNR = \frac{(R_K P_S)^2}{2qF\left[4I_D + (P_S + P_B)R_K\right]B + \frac{16kTBF}{R_L}} \qquad (9)$$

where F is the noise factor, R_L is the transimpedance amplifier feedback resistance (Ω).

In Fig.7, the *SNR* dependence on the P_B, for constant values of P_S: $0.1\,\mu\text{W}$, $1\,\mu\text{W}$, $10\,\mu\text{W}$, and $100\,\mu\text{W}$ is presented. Other parameter values in (9) are: $R_K = 0.45\ \text{A/W}$, $q = 1.602\cdot 10^{-19}\,\text{C}$, $I_D = 100\,\text{nA}$, $k = 1.38\cdot 10^{-23}\ \text{J/K}$, $T = 300\,\text{K}$, $R_L = 80\,\text{K}\Omega$, $B = 10\,\text{MHz}$, $F = 1.2$.

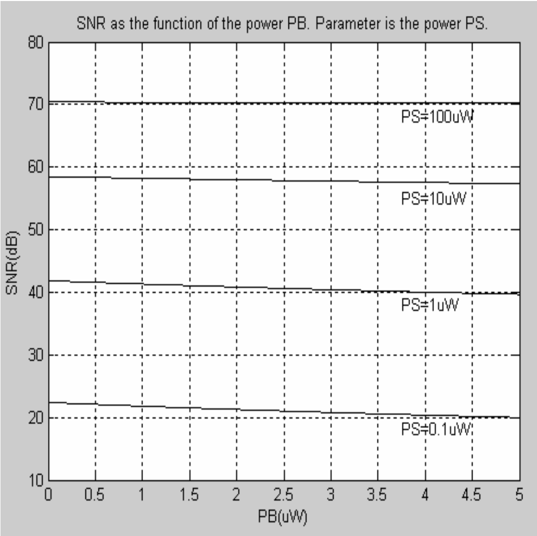

Figure 7. Graphic of SNR as the function of P_B, for parameter $P_S = 0.1$ μW, 1 μW, 10 μW, 100 μW.

From Fig.7, we can conclude that the greatest change in the signal-to-noise ratio (*SNR*) follows the great change of P_B, when P_S is less than or order of P_B. The maximal change of *SNR* of about 2 dB is obtained for $P_S = 0.1$ μW. As the power P_S become greater than P_B, so the influence of P_B on the signal-to-noise ratio decreases. For $P_S \geq 100$ μW, the influence of P_B on *SNR* is negligible. It can be concluded, that it is very important to eliminate the influence of the background power in laser systems, for obtaining greater signal-to-noise ratio and signal detection high-quality.

Conclusions

On the bases of the theoretical considerations, calculated solar spectral irradiance on the Earth surface and measured spectral reflectance for various materials, a great dynamics of received background optical power in 24 hours is obtained. The solar irradiance on the Earth surface depends on geometric Sun-Moon-Earth configuration and atmospheric conditions. It is shown that the changes of the irradiance on the Earth surface in 24 hours, are order of 10^5. Apart from this, the reflectance is changed about 10 times, depending on the kind of natural materials.

The calculated dynamics of about 127 dB, does not include the influences of the receiver parameters. We have to perform the spectral solar irradiance measurements and analyze the experimental data.

The influence of background signal on the signal-to-noise ratio in the presence of the active signal (the reflected laser radiation from object), is also investigated. The great change of the received background power is important only if the signal power is small, i.e when $P_S \approx P_B$.

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Zavisnost odnosa signal-šum od primljene snage od objekta i pozadine u laserskim sistemima

Analiziran je uticaj sunčevog zračenja i koeficijenta refleksivnosti površine na primljenu snagu od pozadine i objekta u laserskim sistemima, koji rade na talasnoj dužini 1,064 μm. Na nivo primljene snage od pozadine i objekta, koji se nalaze u vidnom polju prijemnika, utiče promena iradijanse od Sunca, transmisija atmosfere, kao i koeficijent refleksivnosti površine objekta i njegove okoline. Promena nivoa primljene snage šuma izražena je dinamikom, koja iznosi oko 127 dB, na mestu objekta. Nivo primljene optičke snage reflektovane od objekta i okoline određuje odnos signal-šum u prijemniku. Analizirana je promena odnosa signal-šum (SNR) za konstantnu vrednost primljenog reflektovanog laserskog zračenja (P_S), u funkciji promene snage pozadine (P_B). Promena odnosa signal-šum je maksimalna za $P_S \approx P_B$ i iznosi oko 2 dB.

Ključne reči: **laseri, optička snaga, zračenje sunca, uticaj zračenja, refleksija svetlosti, koeficijent refleksije, iradijansa, odnos signal-šum**

La dépendence du rapport signal-bruit de la force reçue de l'objet et de l'arrière-plan dans les systèmes laser

On a analysé l'influence du rayonnement solaire et le coefficient de reflexivité de surface de la force reçue de l'arrière-plan et de l'objet dans les systèmes laser travaillant sur la longueur d'ondes de 1,064 μm.Au niveau de la force reçue de l'arrière-plan et de l'objet situés dans le champ visuel du récepteur, on constate l'influence du changement de l'irradiance solaire, transmission de l'atmosphère ainsi que le coéfficient de réflexivité de la surface d'objet et de son environnement. Le changement du niveau de la force reçue de bruit est exprimé par la dynamique qui est environ de 127 DB sur place de l'objet. Le niveau de la force optique reçue reflétée à partir de l'objet et de son environnement détermine le rapport signal-bruit dans le récepteur. Le changement du rapport signal-bruit(SNR) pour la valeur constante du rayonnement reflété reçu est analysé en fonction du changement de force de l'arrière-plan (PS). Le changement du rapport signal-bruit est maximal pour Ps=Ps et il est de l'ordre de 2DB.

Mots clés: **laser, force optique, rayonnement solaire, influence de rayonnement, réflexion de lumière, coefficient de réflexion, irradiance, rapport signal-bruit**

Зависимость отношения сигнал-шум от потребляемой мощности от объекта и фона в лазерных системах

В этой работе анализировано влияние солнечного излучения и коэффициента отражения поверхности на потребляемую мощность от фона и объекта в лазерных системах, которые работают на волновой длине **1,064 μm**. На уровень потребляемой мощности от фона и объекта, которые находятся в поле зрения приемника, влияет изменение иррадианса от Солнца, трансмиссия атмосферы, а также и коэффициент отражения поверхности объекта и его окружения. Изменение уровня потребляемой мощности шума выражена динамикой, которая составляет приблизительно **127 dB**, на месте объекта. Уровень потребляемой оптической мощности, отраженной от объекта и окружения, определяет отношение сигнал-шум в приемнике. Здесь анализировано изменение отношения сигнал-шум для постоянной величины потребляемого отраженного лазерного излучения (P_S), в качестве изменения мощности фона (P_B). Изменение отношения сигнал-шум максимальное для $P_S \approx P_B$ и составляет приблизительно 2 **dB**.

Ключевые слова: лазер, оптическая мощность, солнечное излучение, влияние излучения, отражение света, коэффициент отражения, иррадианс, отношение сигнал - шума